High Gradient RF: models and experiments

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Fermilab
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Outline

Model

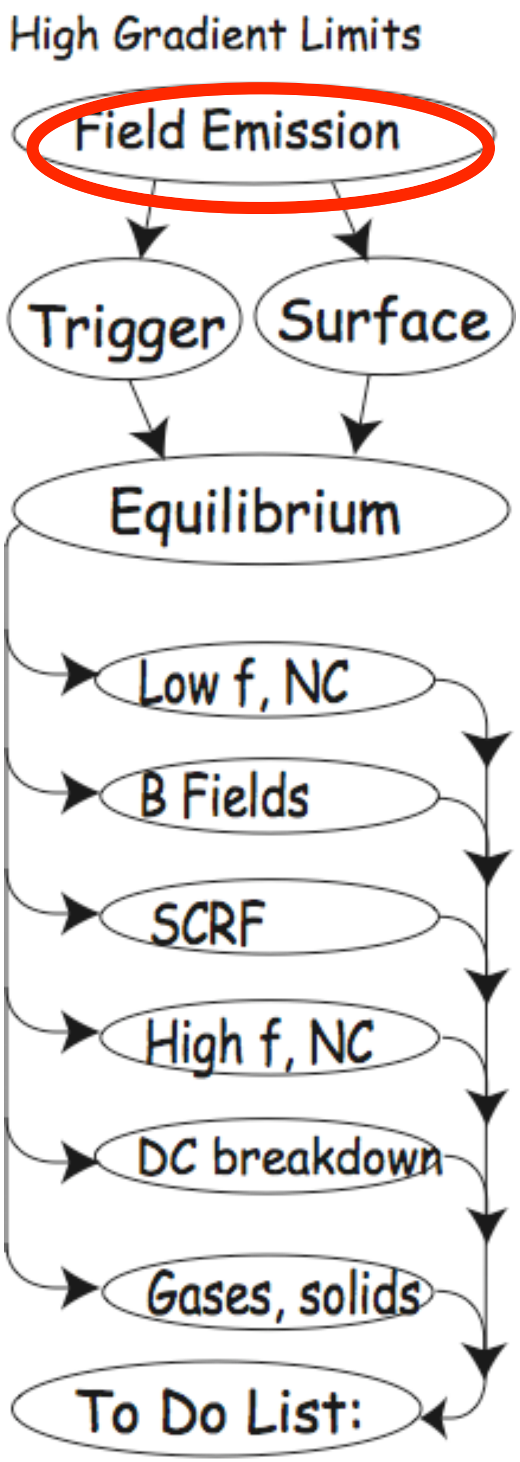
- We have one that seems necessary and sufficient
  - Other effects: Who knows ?
  - Other models: P. Wilson, R. Latham, G. A. Mesyats ?

Data

- Curiously little relevant data is available
  - Lots of redundant data – more coming.
- Diverse experiments would be more productive

R&D Effort

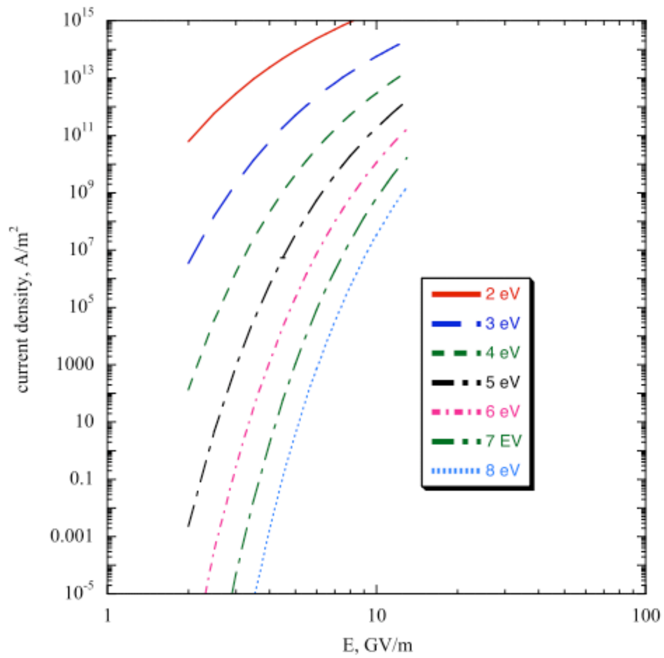
- Understanding limits crucial to energy frontier machine design.
- Historically neglected
- DC, High Freq, Low Freq, SCRF all closely related.
- Fermilab should be in this.

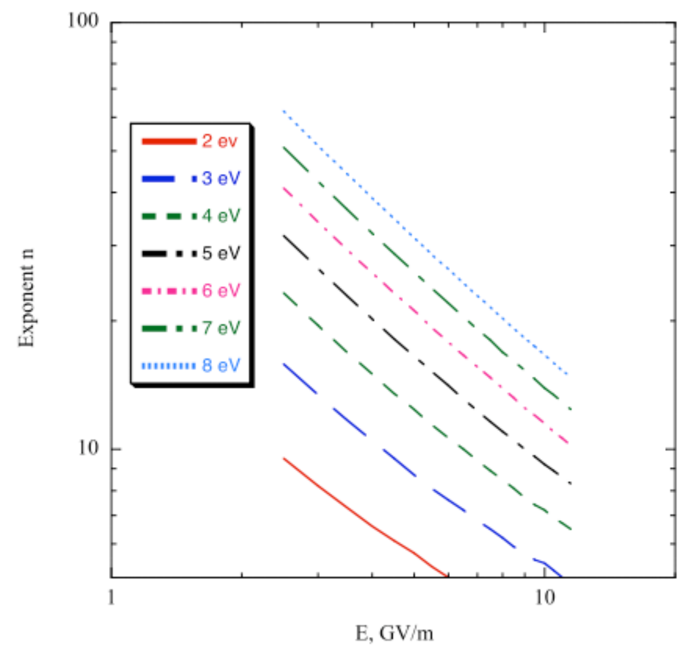


- Field emission defines the local environment

$$I(E_{local}) = A_{area} A_{rf} \frac{1.5 \times 10^6}{\phi} E_{local}^2 \; exp\left(\frac{10.4}{\phi}\right) exp\left(\frac{-6440\phi^{3/2}}{E_{local}}\right)$$

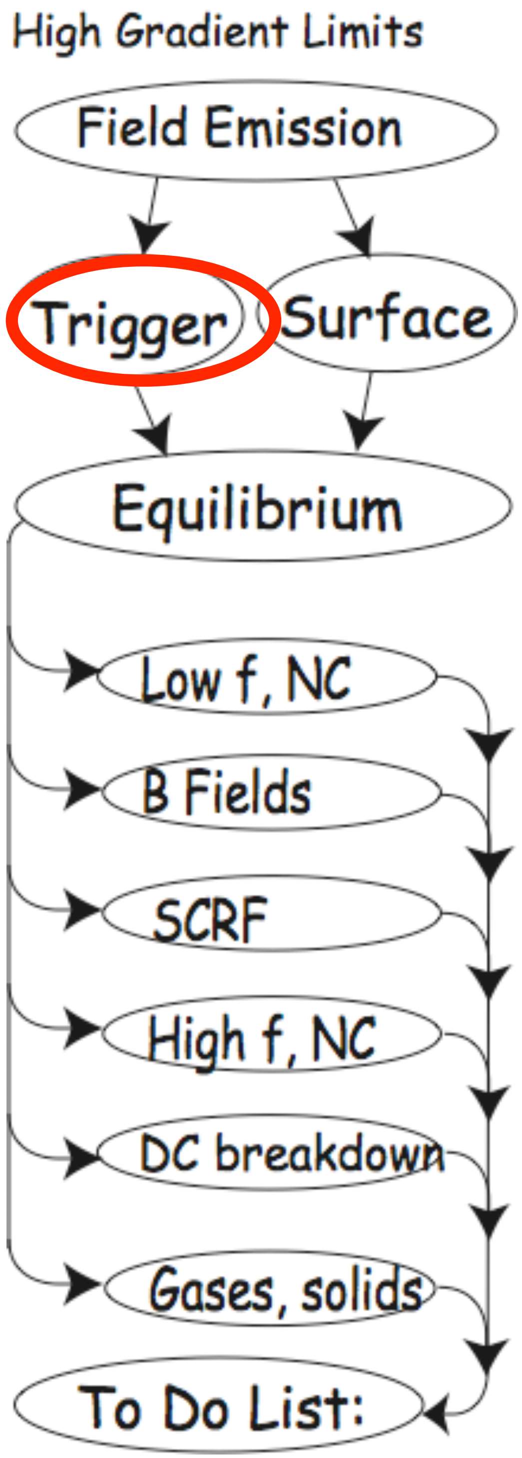
- Describes what we see, $I \sim E^n$.





- All DC & rf measurements imply E_{local} < 10 GV/m.

- The simple picture is complicated by surface chemistry.



- Electric fields produce large $\varepsilon_0 E^2/2$ stresses.

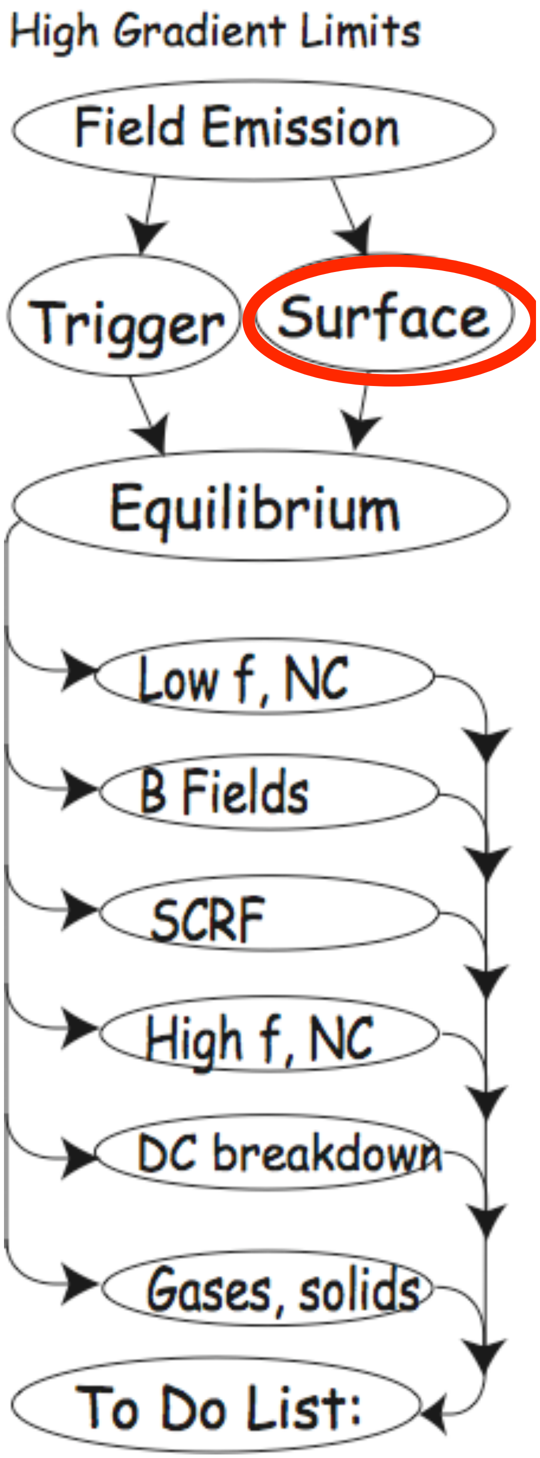
- A well known effect 

- Fatigue also contributes.

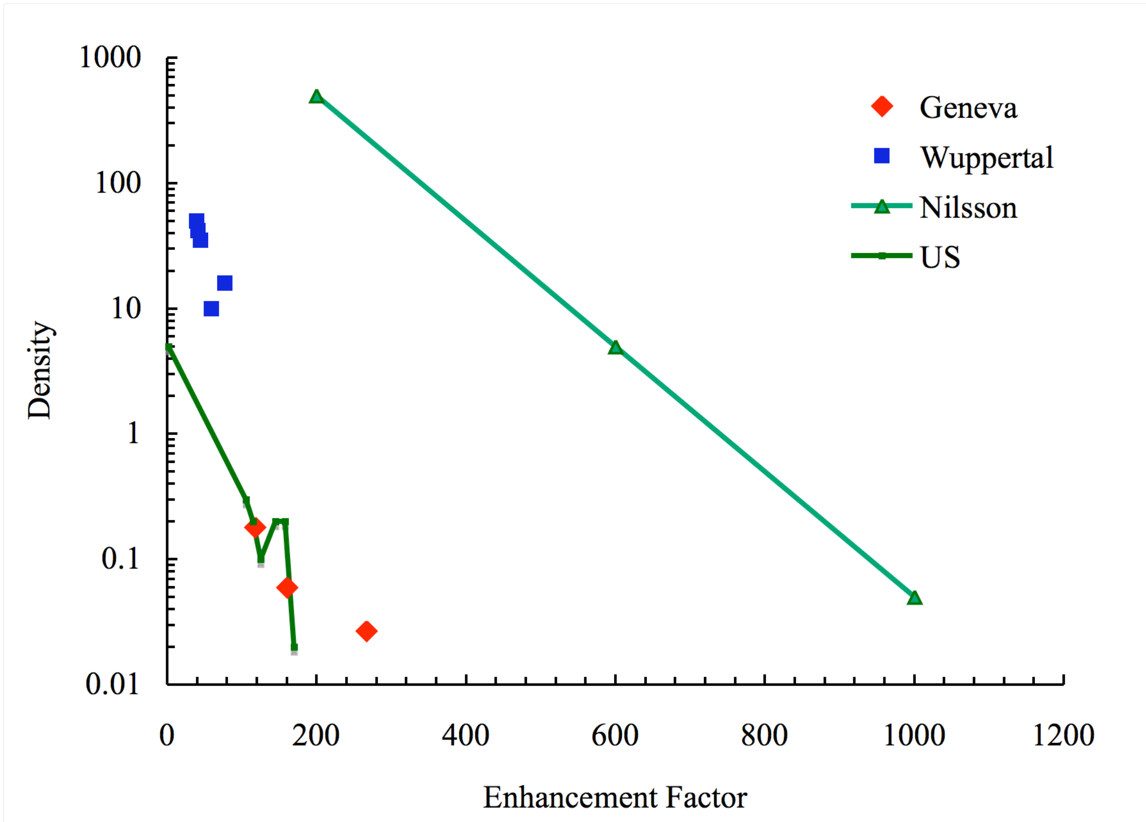
- Atom probe tomography uses this effect to disassemble materials, atom by atom – at higher fields.

- There is a discontinuity @ 7 – 10 GV/m, where tensile stress ~ tensile strength

- This should not be surprising.

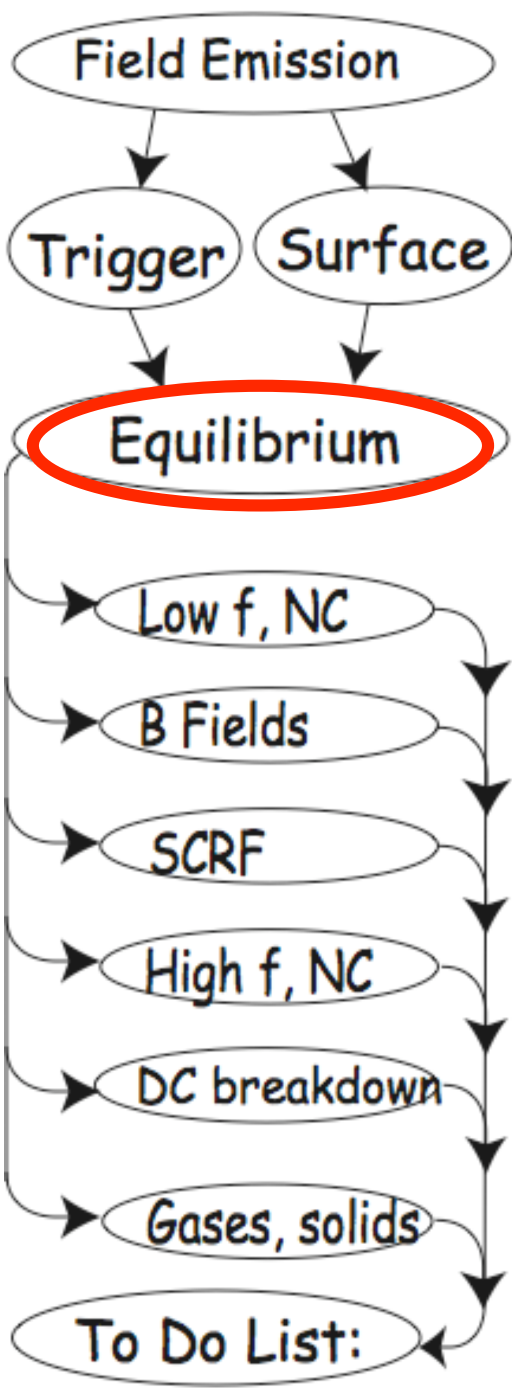


- Large field enhancements, β, occur naturally.
- They come from contamination, damage, etc.



- Seen by everyone who looked (except SLAC).
- Need more data from Field Emission Microscope, and cavity data to understand spectra.

High Gradient Limits



- An equilibrium develops, with high β's cut off.
  Material scientists want this.

- This gives distributions like, (Nilsson JAP 90 (01) 768)

$$s_3(\beta) = \frac{5 \times 10^7 exp(-0.1\beta)}{1 + exp(\beta - 132)}$$

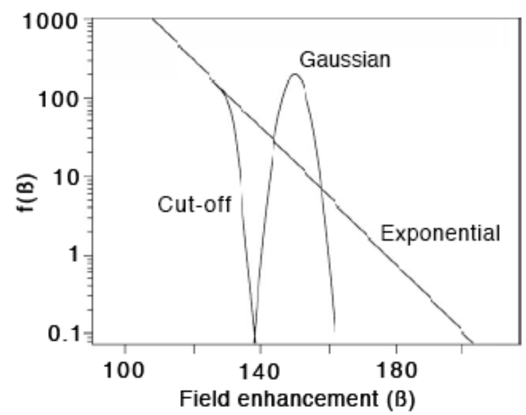
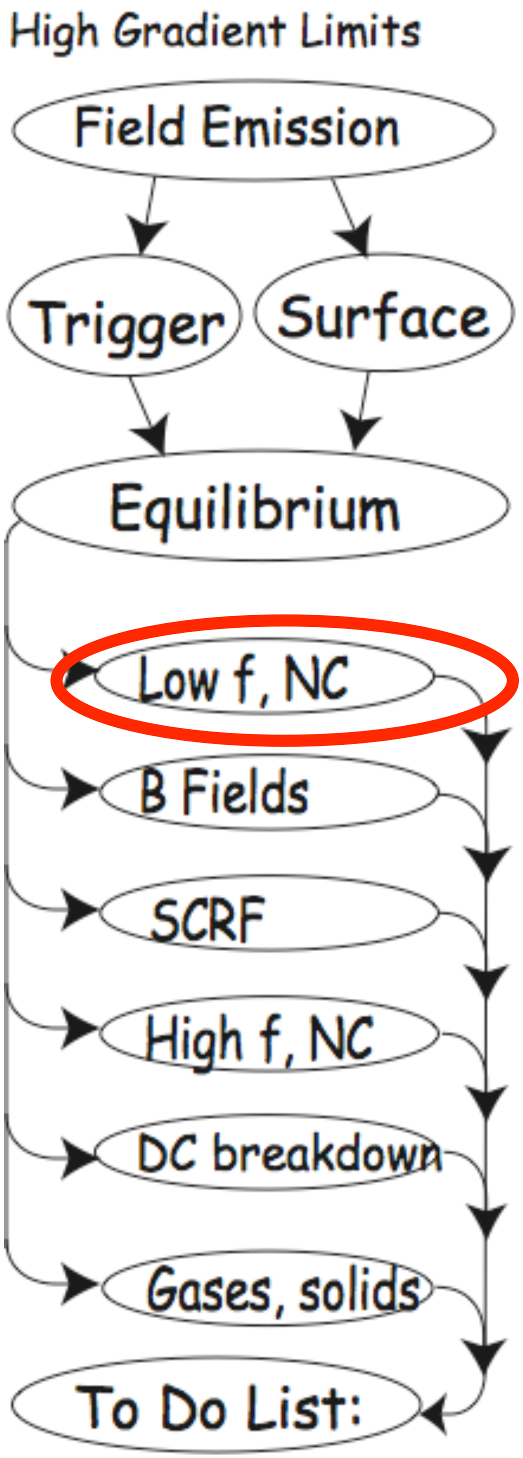


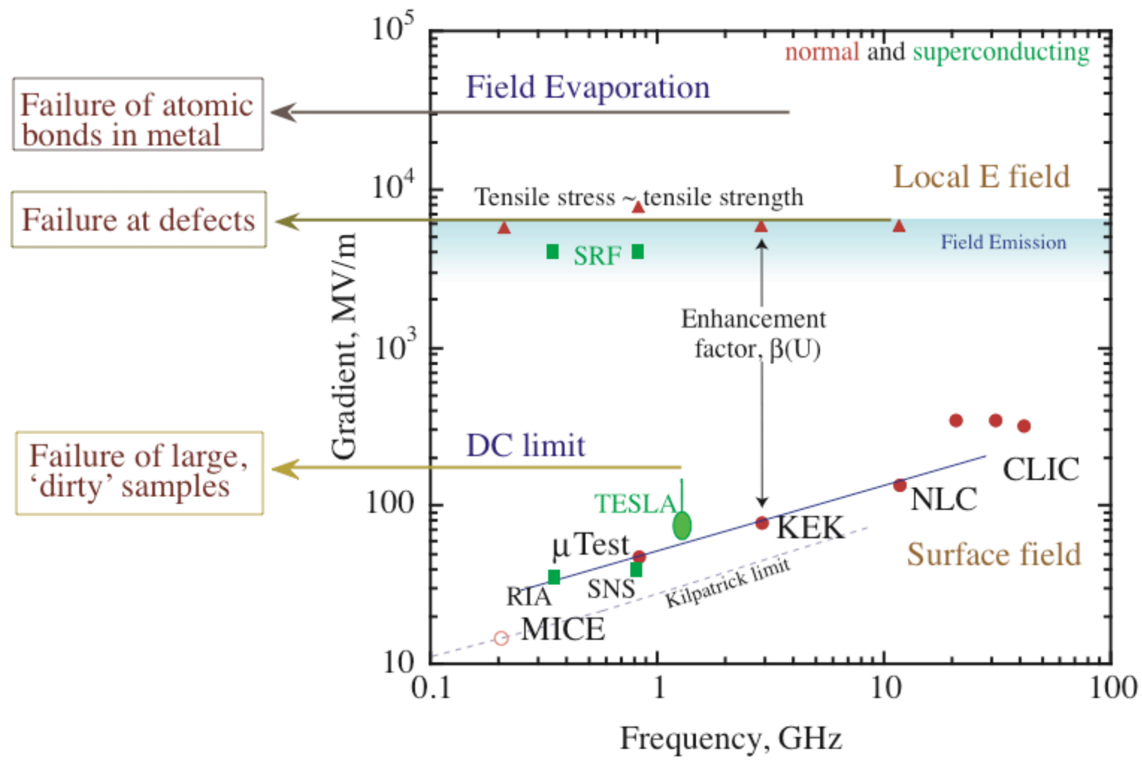
FIG. 1. Simulation of three β distributions. The Gaussian $f(\beta)$ with idealized narrow spread of field enhancement values. The exponential $f(\beta)$ with decreasing density of sites. The cutoff $f(\beta)$ is obtained from the exponential distribution if the highest field enhancement FES are removed.

- We see these distributions – different constants.

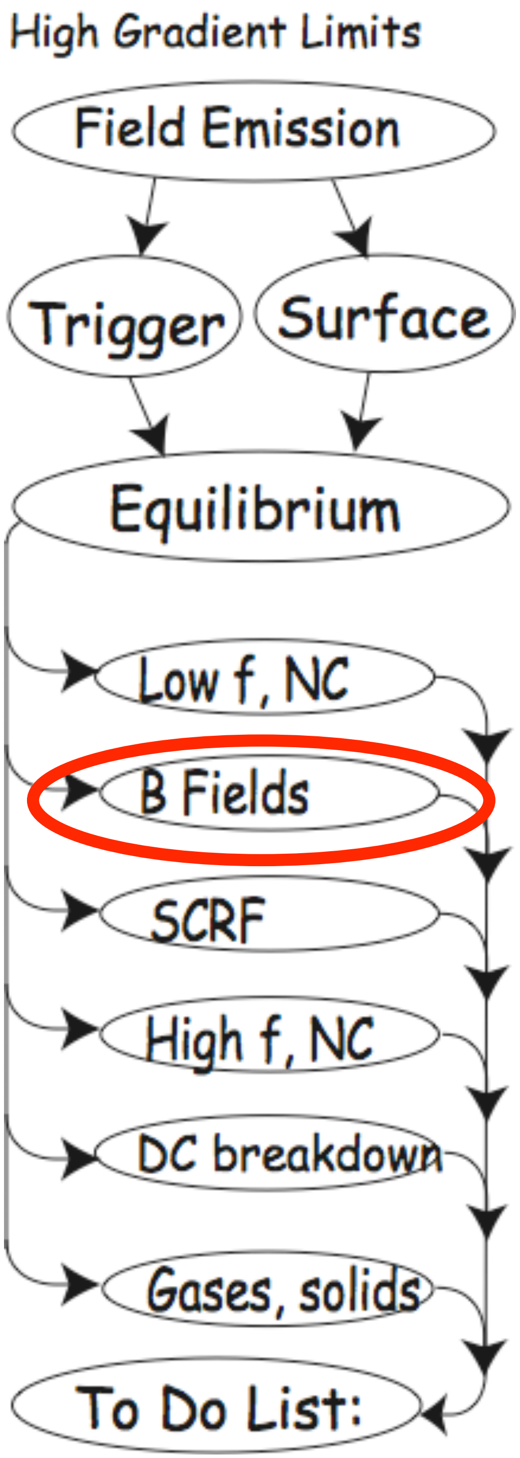
- Higher stored energy ⇔ higher enhancements.



- Maximum cavity fields are given by $E_{max} \sim$ (Tensile str. Limit) / $\beta_{equil}(E)$

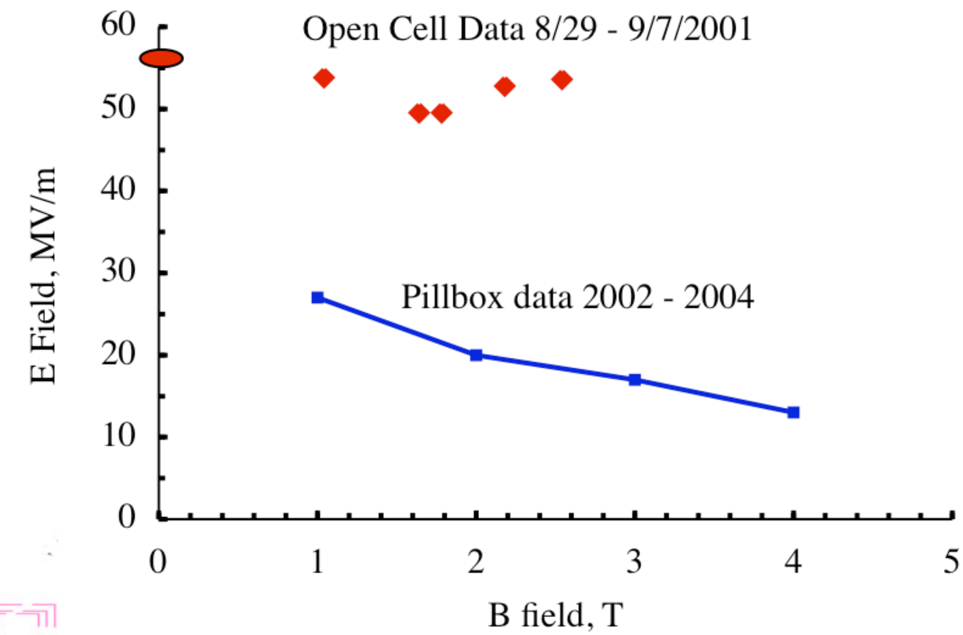


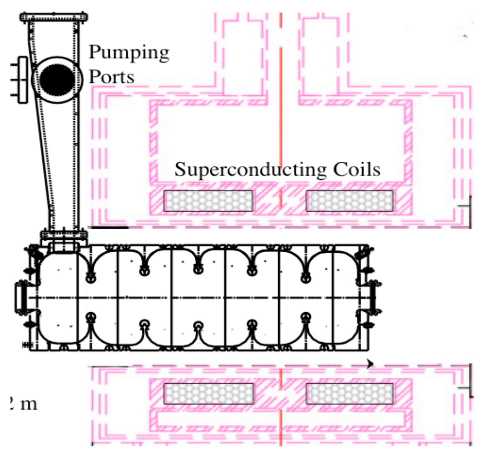
- Also predicts pulse length behavior, conditioning etc., etc.



- B fields are a major problem for muon cooling.

- Data seems to show geometry dependence.

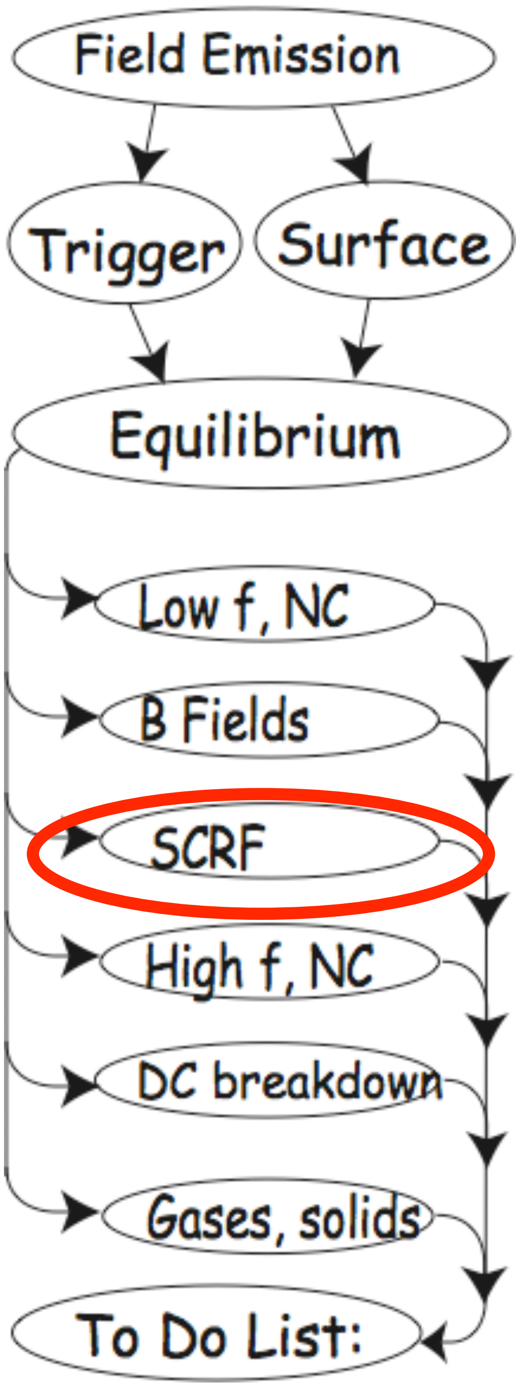




Open cell cavity

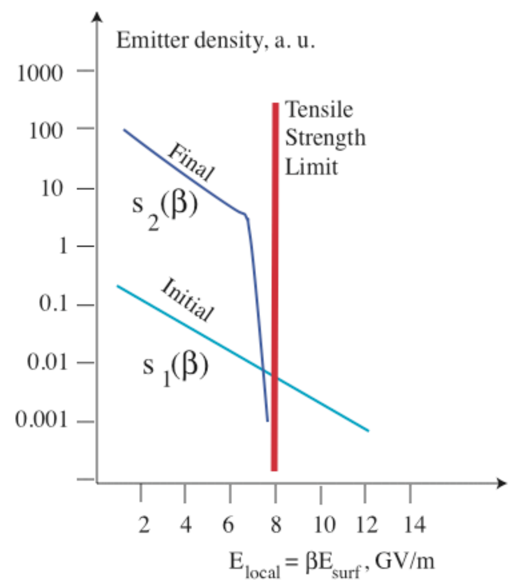
- We need to understand this.

High Gradient Limits

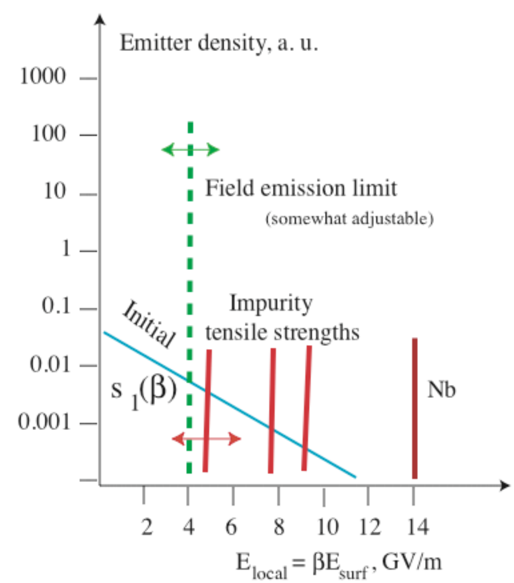


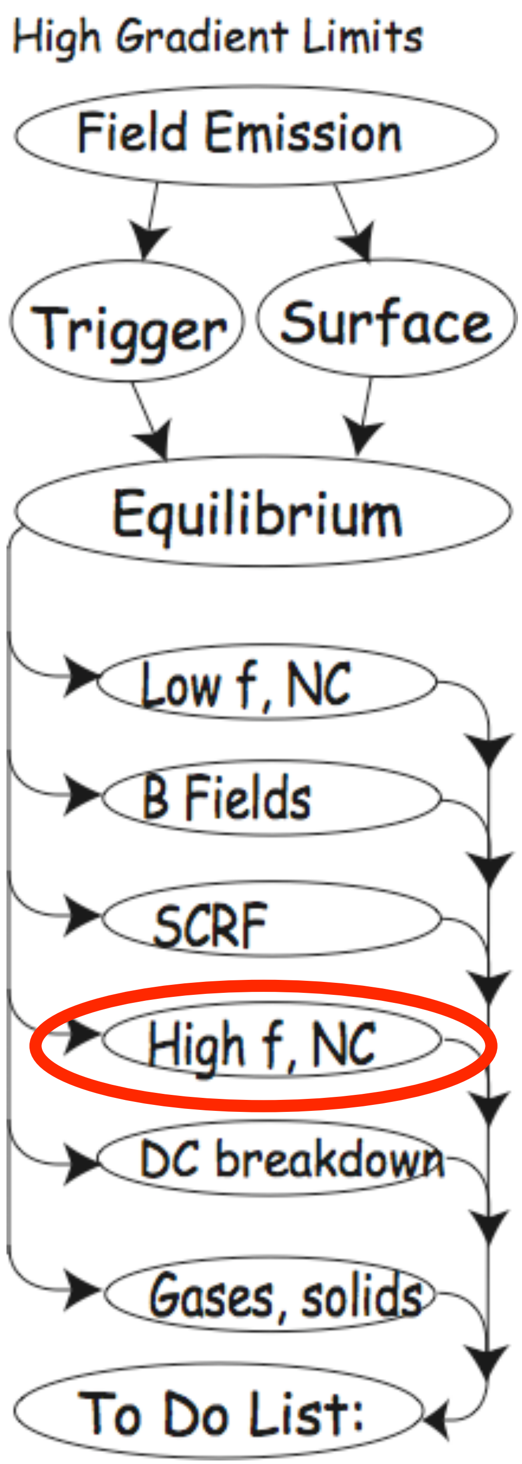
- SCRF sees the same problems with β's.
- Their "high pulsed power conditioning" is what we do, however their cavities overheat before they can remove most emitters/breakdown sites.
- Field emission prevents conditioning

Copper

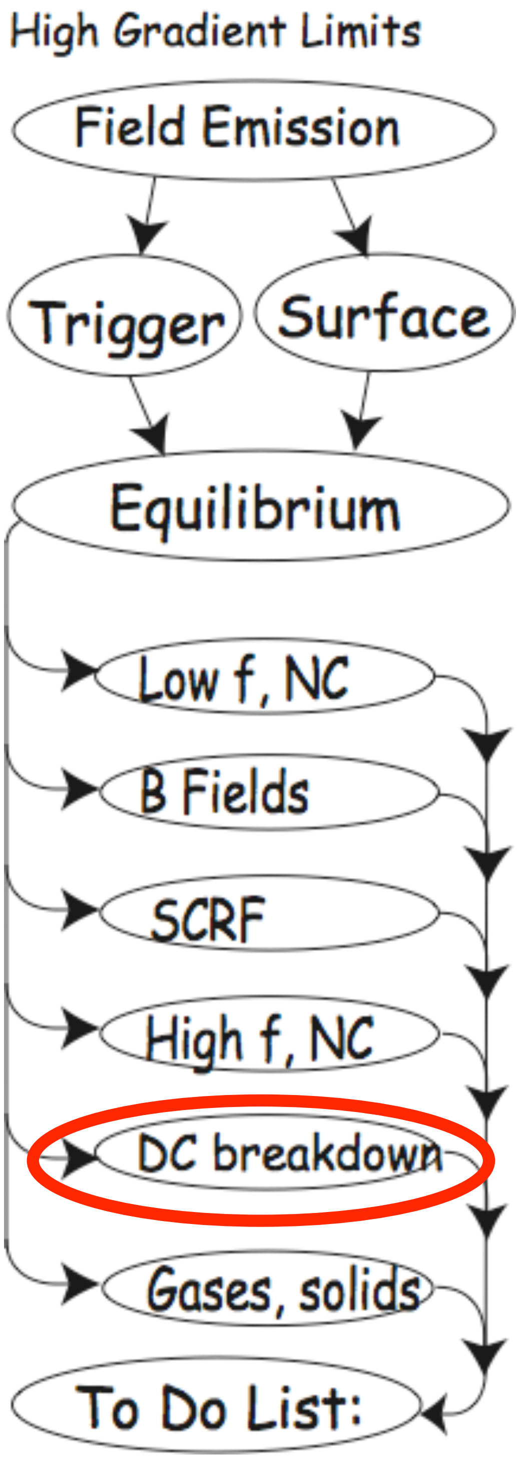


SCRF





- High Frequency cavities see "pulse heating"
- Low frequency cavities are not generally sensitive to this.
- A 100^0 surface temperature rise is bad.

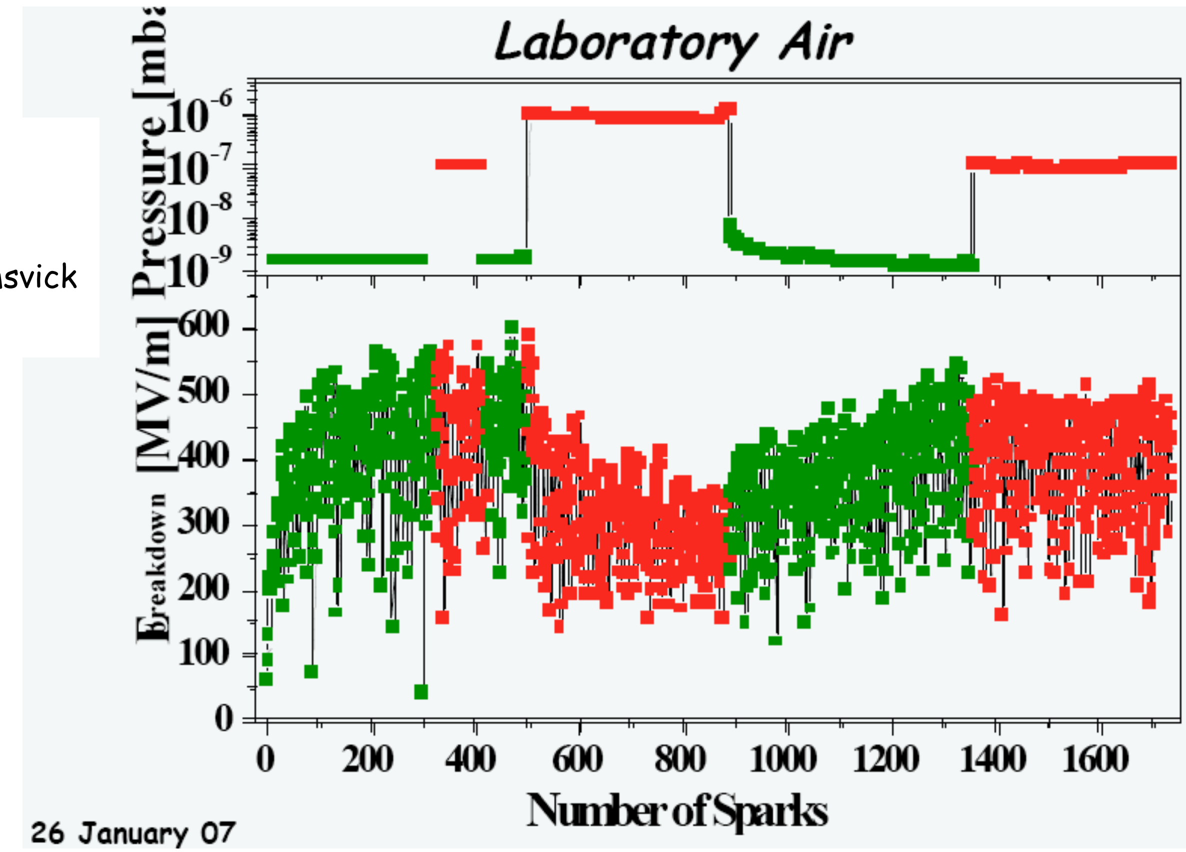


- Recent DC studies (CERN) show that many materials are sensitive to gas pressure (oxides)

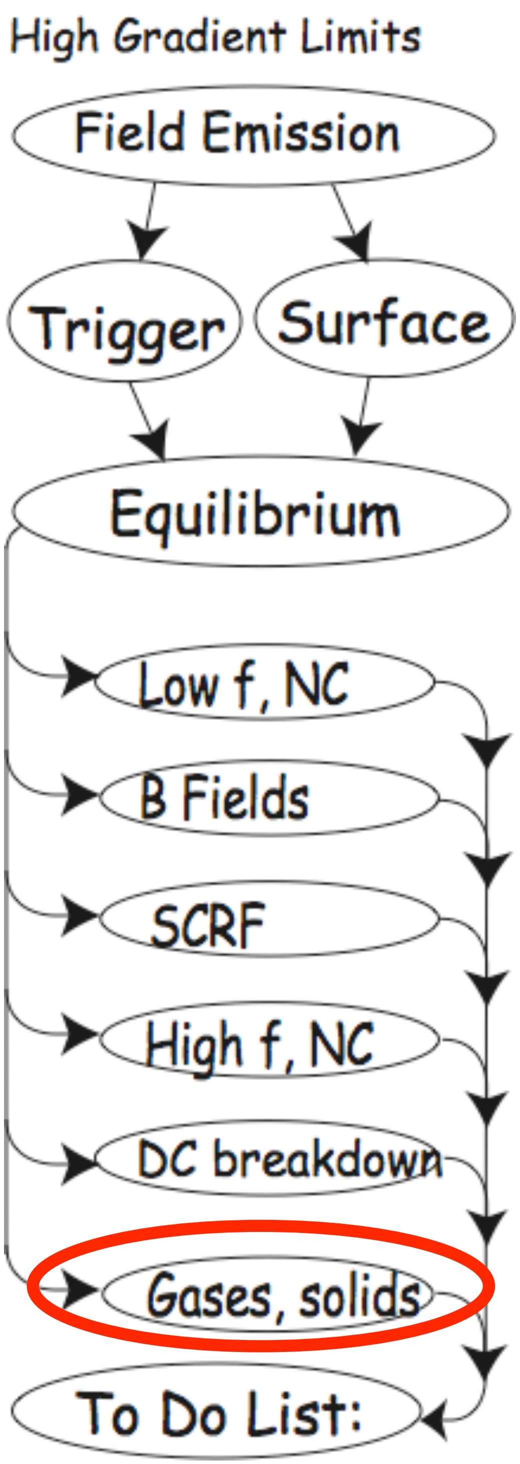
- Copper doesn't seem to be comparably sensitive

Mo

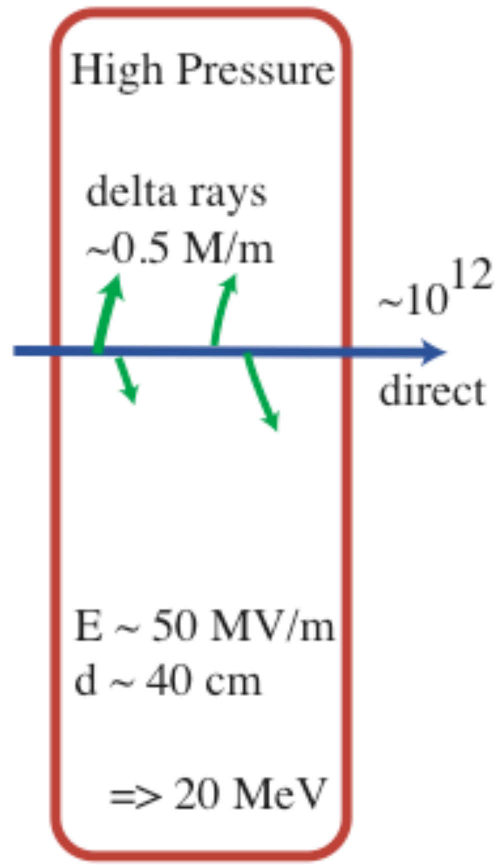
T. Ramsvick

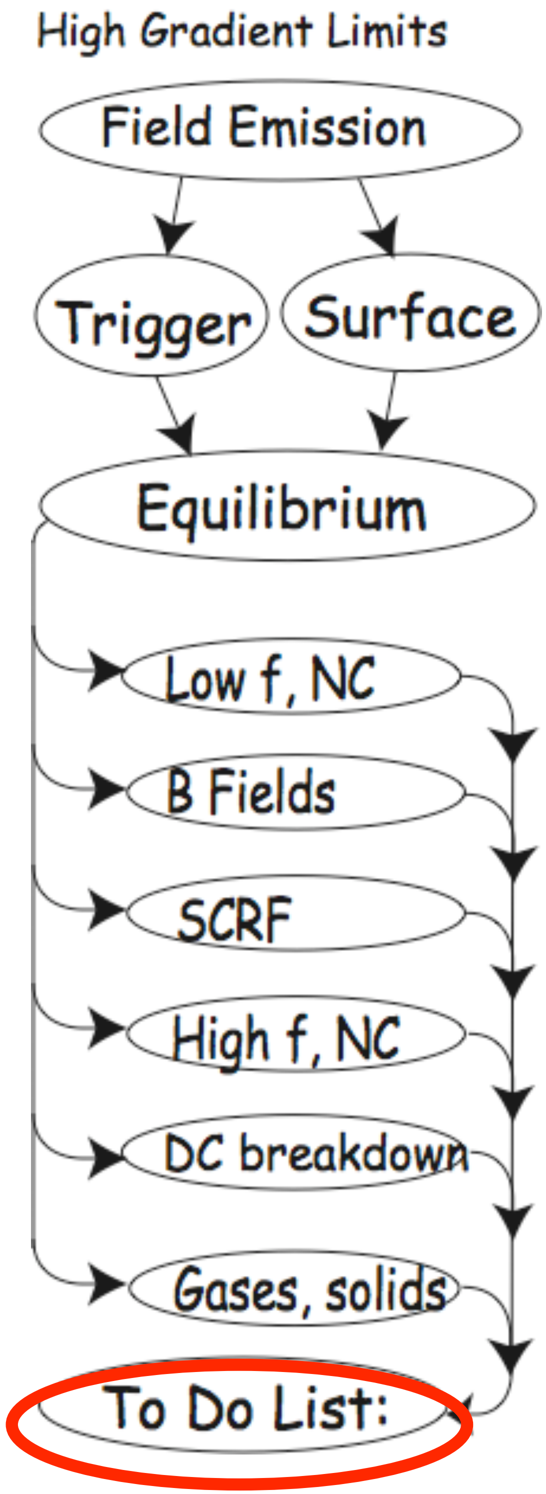


- Oxides complicate modeling breakdown.



- High Pressure & Dielectric response to beams is complex.
- Ionization/recombination/runaway electrons can affect the accelerating structure.





- Some things to do:
  - E X B effects
  - High pressure studies at synchrotrons
  - Field emission microscopy
  - Atom Probe studies of materials
  - Low energy gas theory
  - Beam loading
  - Plasma Arc studies

1) E X B effects are important.

- Magnetically insulated transmission lines work.
- We need the MICE coupling coil.
- A rotatable cavity would be very useful, and give basic data.
- The design is tricky,
  Moretti needs a challenge.

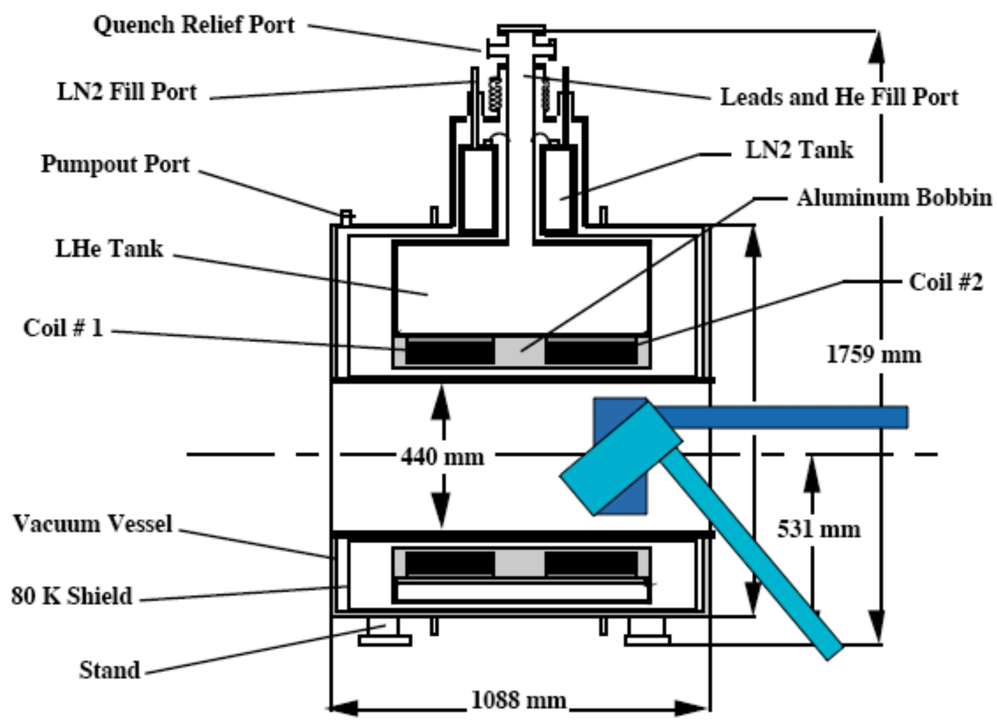
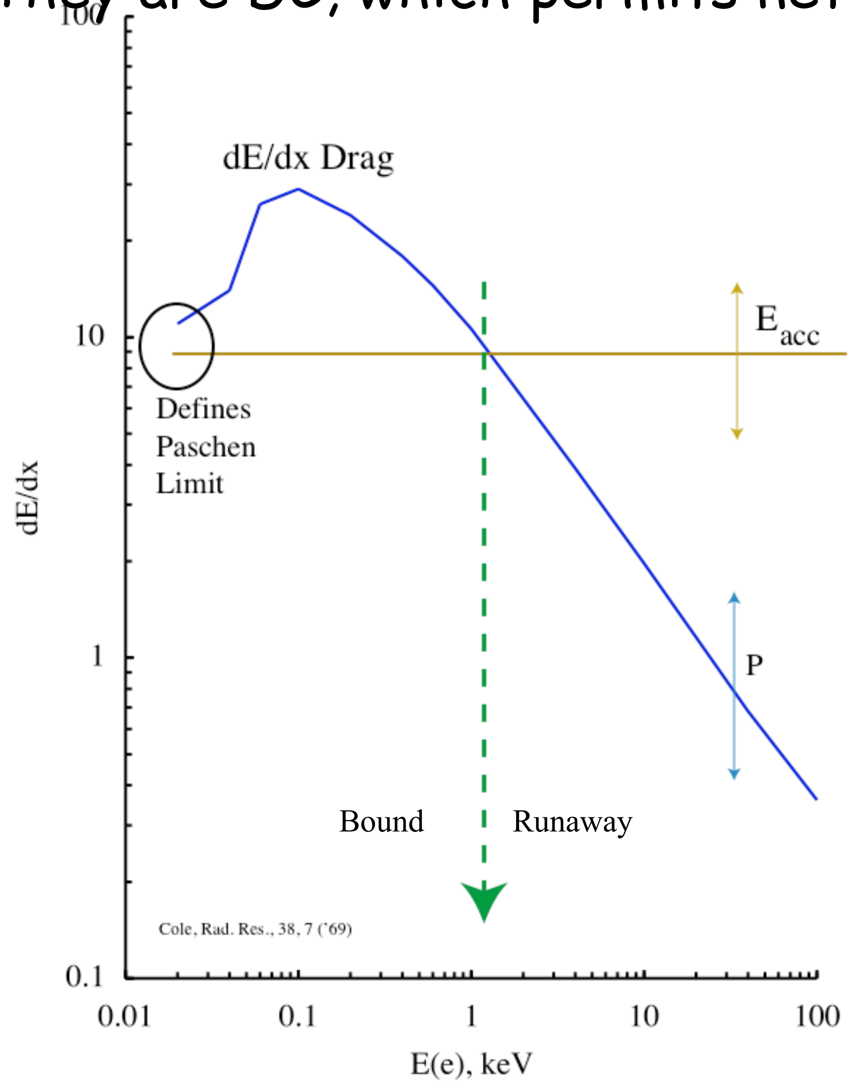


Figure 1. A Cross-section View of the RF Solenoid from the Side

2) High pressures and dielectrics.

- Beam effects may be easier to study in synchrotron beams.

- They are DC, which permits network analyzer measurements



3) Field emission Microscopy

- This seems to be the best way to study emitters/breakdown sites.

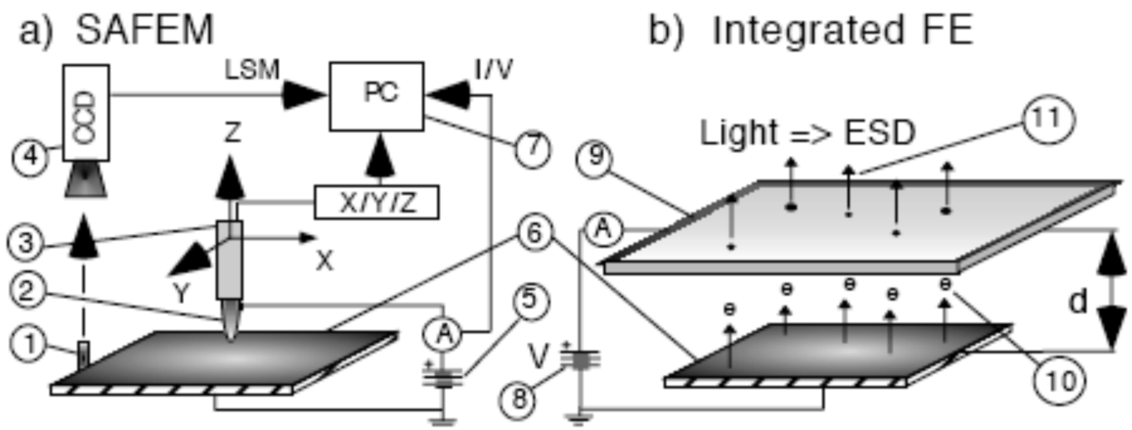
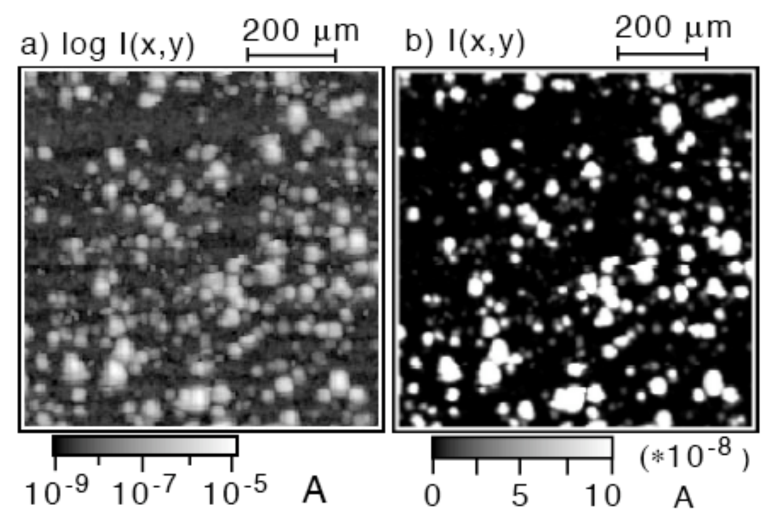


FIG. 4. FE apparatuses: (a) Scanning anode field emission microscope and (b) integral field emission with a phosphor screen. (1) Reference light source for sample positioning. (2) *x/y/z*-movable scanning FE Pt–Ir tip (radius ~5 μm). (3) *x/y/z* piezo step motors. (4) Charge coupled device camera for motion monitoring. (5) Source-measure device (1100 V/10 mA). (6) Carbon thin film emitter. (7) Computer controlled sample motion, current (*A*) and voltage (*V*) monitoring. (8) High voltage supply 3000 V. (9) Phosphor screen with variable separation *d*. (10) Spotwise electron emission. (11) Electron stimulated fluorescence of the phosphor screen ⇒ emission site density.

(Nilsson JAP 90 (01) 768)



4) Atom Probe Tomography

- This is the ideal way to study high fields + materials.

- 21st century technology.

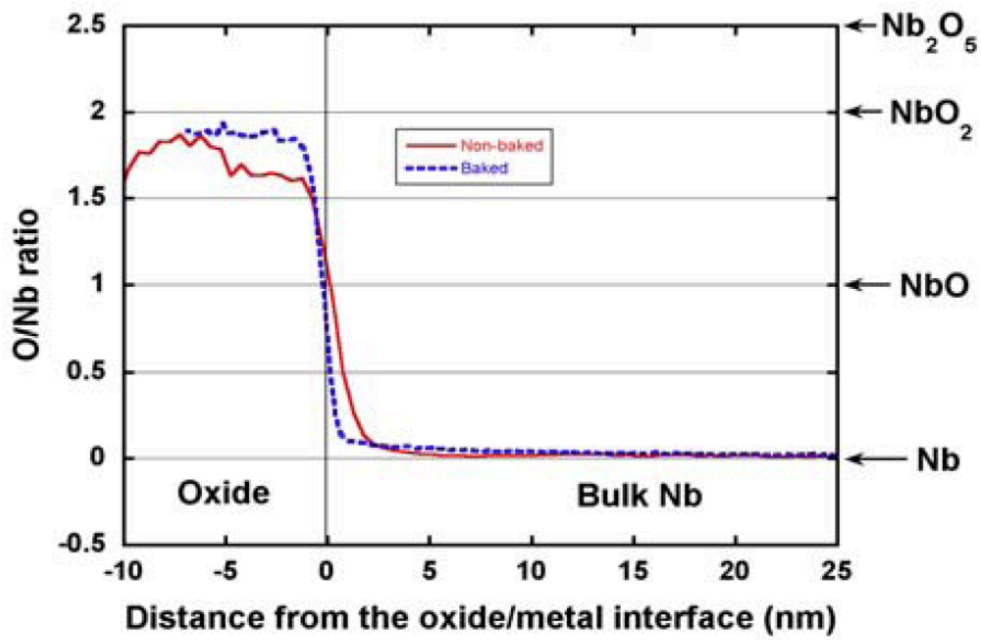


Fig. 5. O/Nb ratio from the 3D reconstructions of unbaked and baked niobium tips. The stoichiometry of the oxide is deduced from the profile. The profile clearly demonstrates that the thickness of the oxide decreases after baking. The chemistry of the oxide, however, does not change.

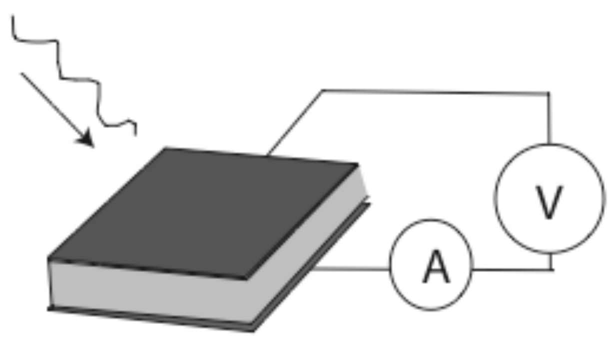
5) Gas/dielectric breakdown theory

- Drift chamber physics and breakdown mechanisms have a lot in commom.

- Much of this is in standard programs and references.

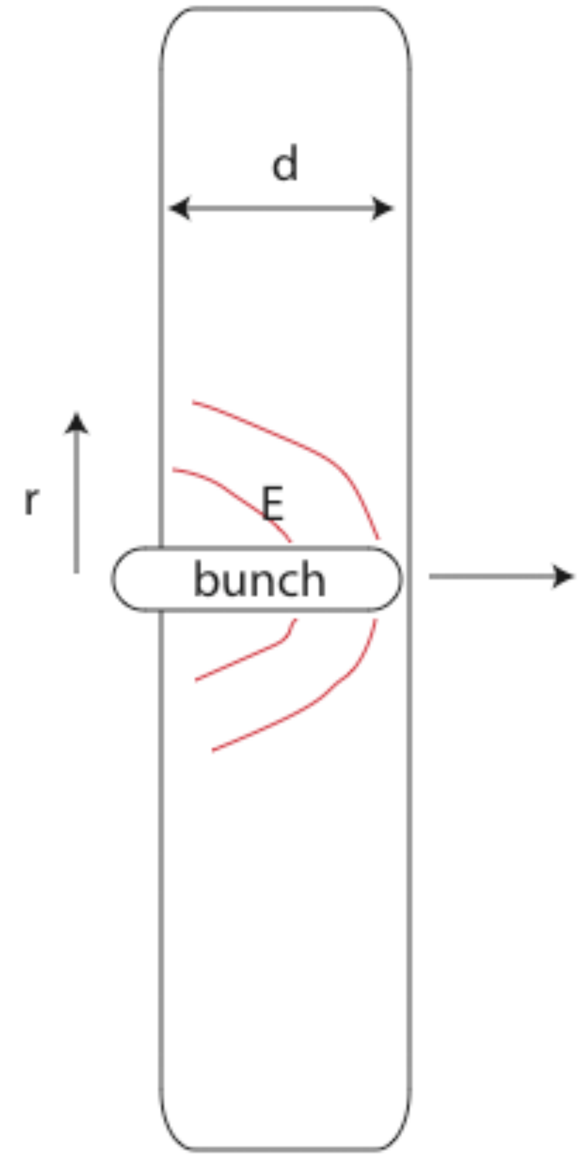
- Are tests with beams/solids relevant?

- What has been done?



6) Beam loading

- This could be an issue for the small beams required by colliders.
- The bunch can only take energy from the part of the cavity that causally communicates with it, r ~ d.
- Trailing edges of the bunch can see reduced accelerating fields.
- Loading heats the beam.



7) Nanofabricated SCRF Composites

- **How structures fail**

<u>Field emission</u>

Field emitted electrons heat and quenches the superconductor.

<u>Multipactor</u>

Resonant amplification of low energy electrons.

<u>Quench fields</u>

Cavities quench when

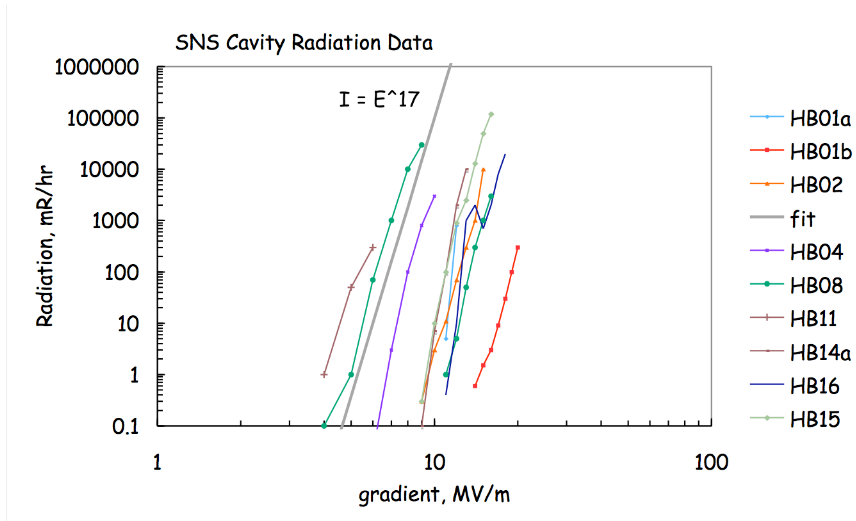
$B > 180$ mT

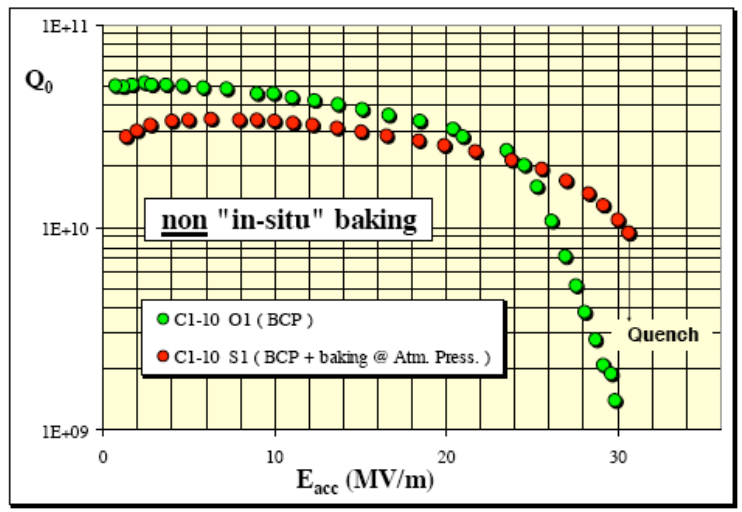
<u>High field Q-slope</u>

Cavity losses rise with impurities and defects.

<u>Thermal</u>

Increased thermal conductivity stabilizes quenches.





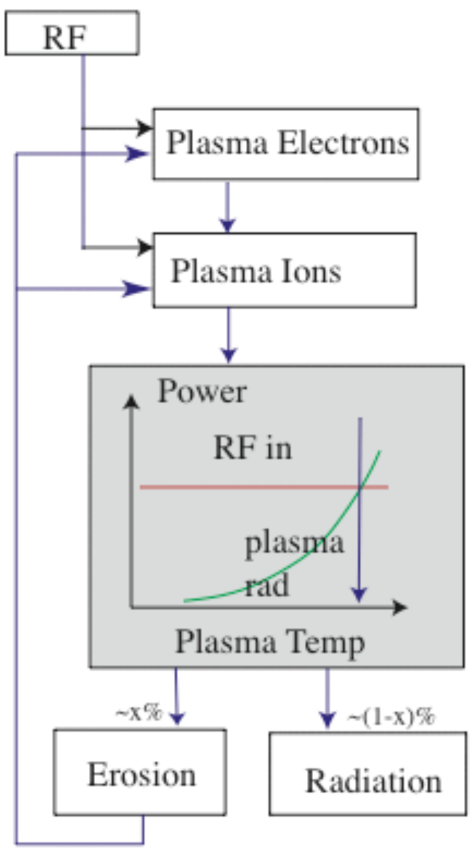
- Can one design materials that can't fail in these ways?

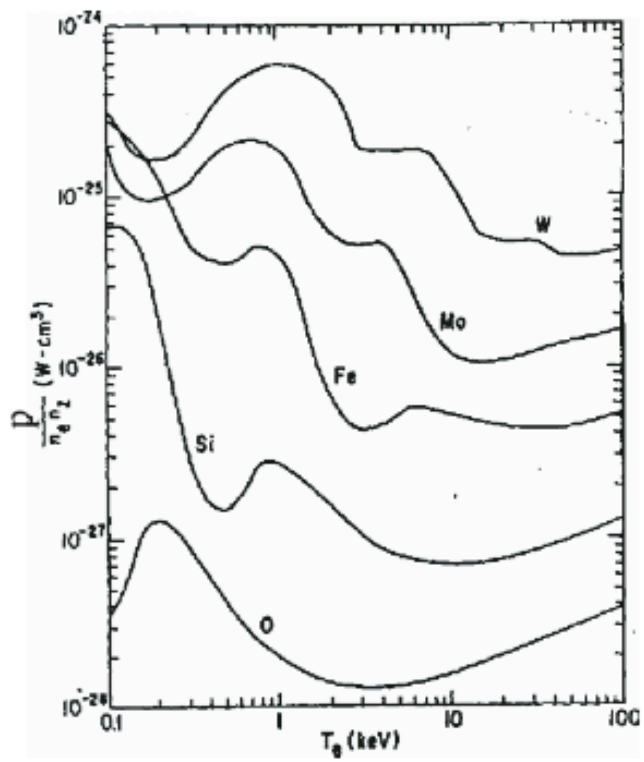
8) The plasma physics of the discharge has not been explored.

- In a dense, metallic plasma, recombination radiation (called impurity radiation in the fusion community) seems to be the dominant effect & is not well understood.

- Arcs happen fast, and ions don't drift far ⇒ very dense plasmas

- An effort to understand arcs is underway with Tech-X





Summary

- Accelerator science needs to understand rf gradient limits.
- I think the program centered at SLAC is starting in the wrong place and going in the wrong direction.
- Unlike engineering development projects, a research program will have little natural momentum, and primarily requires people interested in understanding many mangy issues.
- SCRF, High Pressure, Magnetic fields, Vacuum, High and low f are all part of the same field.
- Fermilab should contribute.